# Top Quark Mass in Lepton+Jets Decays at the Tevatron

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Various measurements of the top quark mass in the lepton+jets decay channel of top quark pair production are presented. The measurements are performed on data samples of up to 2.7 $\text{fb}^{-1}$ of integrated luminosity acquired by the CDF and DØ experiments in Run-II of the Tevatron proton-anti-proton collider at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. The new Tevatron combination using up to 2.8 $\text{fb}^{-1}$ of data results in a preliminary world average mass of the top quark of $m_{\text{top}} = 172.4 \pm 1.2$ GeV. This corresponds to a relative precision of 0.7%.

## 1. Introduction

The top quark was discovered in 1995 by the CDF [1] and DØ [2] experiments at the Fermilab Tevatron proton-antiproton collider. The mass of the top quark, which is by far the heaviest of all quarks, plays an important role in electroweak radiative corrections and therefore in constraining the mass of the Higgs boson. Precise measurements of the top quark mass provide a crucial test of the consistency of the Standard Model (SM) and could indicate a hint of physics beyond the SM.

The Tevatron is still the only place where top quarks can be produced and studied directly. At the Tevatron, top quarks are mostly produced in pairs via the strong interaction. In the framework of the SM, the top quark decays to a $W$ boson and a $b$ quark nearly 100% of the time. Events from top quark pair production are classified according to the $W$ boson decay channels. An event is referred to as "dilepton" if both $W$ bosons decay leptonically, "all jets" if both $W$ bosons decay hadronically, and "lepton+jets" channel if one of the $W$ boson decays leptonically in either and electron or muon and the corresponding neutrino and the other one hadronically. In this report measurements of the top quark mass in the lepton+jets channel are presented.

## 2. Event Selection

The selected events are required to contain an isolated electron or muon and at least or exactly four jets with high transverse momenta and large missing transverse energy. The dominant background contribution is $W$ boson production with associated jets ($W$+jets). The second largest background is multijet production where a jet is misidentified as a lepton and large missing transverse energy is faked. By identifying $b$ jets in the final state, these background contributions can be substantially reduced.

## 3. Top Quark Mass Measurements

Different methods to measure the top quark mass are discussed. "Template Methods" [3, 4] have the advantage of being more straightforward and transparent but are statistically less accurate. To maximize the statistical information on the top quark mass extracted from the event sample, more elaborated but also more complex methods exist as e.g. the "matrix method" [5, 6], the "ideogram method" [7] or the "dynamical likelihood method" [8]. An alternative method uses the cross section measurement to extract the top quark mass [9]. Some examples are presented here.

### 3.1. Template Method

Distributions of variables that are strongly correlated with the top quark mass are derived as templates in Monte Carlo simulations for different top mass hypotheses. They are compared to the measured distribution in order to

extract the top quark mass from data.

In [3] two variables are used. First, the reconstructed top quark mass $m_t^{\text{reco}}$ is derived by minimizing a $\chi^2$-like function to the over-constrained kinematics of the $t\bar{t}$ system using the measured 4-vectors of the charged lepton and the jets, the measured missing transverse energy and $b$-tagging information. It is summed over all possible assignments of partons to jets. The well-known $W$ mass is used to constrain the invariant mass of the electron/muon-neutrino pair from the leptonic $W$ decay and the dijet mass from the hadronic $W$ decay. The top quark and antitop quark masses are constrained to be equal within the top width. As second variable the dijet mass of the hadronically decaying $W$ boson is used. It constrains the so-called jet energy scale *in situ* which represents the largest systematic uncertainty in top quark mass measurements.

The values of both variables for candidate events with at least 1 $b$-tag are compared to a two-dimensional probability density function derived by applying a kernel density estimation to fully simulated MC events for different values of the top quark mass and jet energy scale. The measurement is performed simultaneously in the lepton+jets and dilepton channels. The 2-dimensional likelihood is presented in Fig. 1 (upper left). As a result, a top quark mass of $m_{\text{top}} = 171.9 \pm 1.7(\text{stat}) \pm 1.0(\text{syst})$ GeV was derived. The total accuracy is thus $\pm 1.1\%$.

## 3.2. Alternative Template Method

To be less dependent on the largest systematic uncertainty of the previous method, in [4] quantities are used with minimal dependence on the jet energy scale. One variable is the transverse decay length of $b$-tagged jets, and the other is the transverse momentum of the lepton. Both quantities are roughly linearly dependent on the top mass. Their combination significantly reduces the statistical uncertainty because the statistical resolution in the top mass determination is similar and they are approximately uncorrelated. As a result, the top quark mass was measured to $m_{\text{top}} = 176.7 \pm 6.2(\text{stat}) \pm 3.0(\text{syst})$ GeV. This corresponds to a total uncertainty of 3.9%. Since the result is statistically limited, it will improve with more data added in the future, or if the measurement is performed at the Large Hadron Collider (LHC).

## 3.3. Matrix Element Method

For the matrix element method a probability is calculated for each event as a function of the assumed top quark mass $m_{\text{top}}$ and an overall multiplicative scale factor JES for jet energies. The factor JES is fitted *in situ* in data, simultaneously with the top quark mass by using information from the invariant mass of the hadronically decaying $W$ boson. For every event, this mass is constrained to be equal to the known value for the $W$ mass. The probabilities from all events in the sample are then combined to obtain a probability as a function of $m_{\text{top}}$ and JES, and the top quark mass is extracted by finding the values that maximize this probability.

The analyses performed by the CDF [5] and DØ [6] experiments are very similar. One main difference is the treatment of background. While in [5] a neural network discriminant is used to distinguish signal from background, in [6] the probability for one event is composed from probabilities not only for top quark pair production signal but also for $W$+jets background.

For both measurements pseudo-experiments using a large pool of fully simulated MC events are performed to calibrate the method, correcting for biases to ensure that the fitted parameters represent true values and that the estimated errors can be trusted. The two-dimensional likelihoods on data events are shown in Fig. 1 (upper right for CDF and lower left for DØ). As a result the top quark mass is measured to $m_{\text{top}} = 172.2 \pm 1.0(\text{stat}) \pm 1.3(\text{syst})$ GeV by CDF [5] and $m_{\text{top}} = 172.2 \pm 1.0(\text{stat}) \pm 1.4(\text{syst})$ GeV by DØ [6]. The total uncertainties for both measurements are $\pm 1.0\%$. They are systematically limited. The largest sources of systematic uncertainties apart from the simultaneous inclusion of JES are given by residual JES, in particular of $b$-jets, and theoretical uncertainties in signal and background modeling. Currently both experiments are undertaking large efforts to get a uniform treatment of all uncertainties where ever possible.

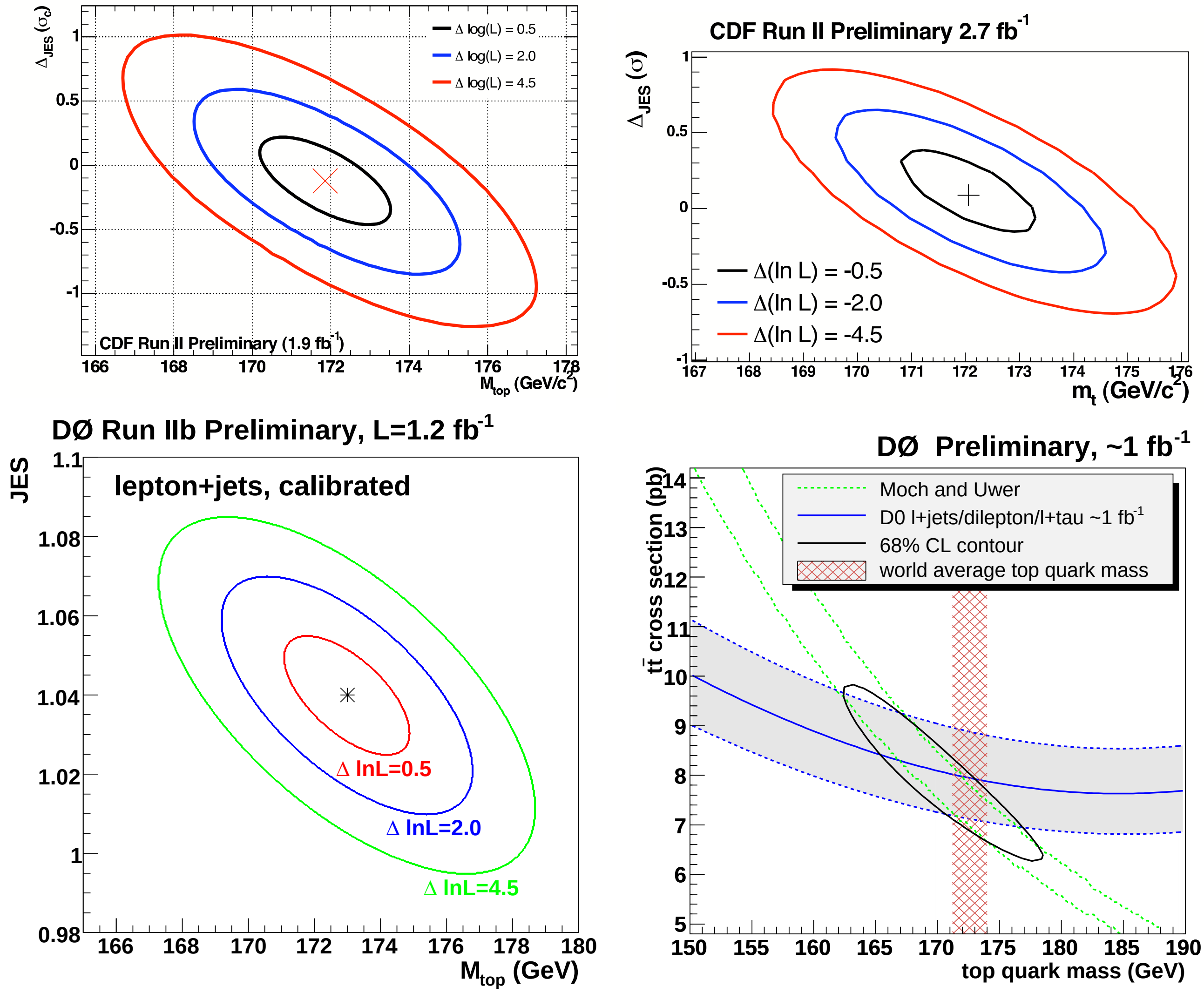


Figure 1: 2D-likelihood on data events including the $1\sigma$, $2\sigma$ and $3\sigma$ uncertainties for the CDF template method [3] (upper left), the CDF matrix element method [5] (upper right) and the DØ matrix element method [6] (lower left). The latter was derived from a subsample of 1.2 fb$^{-1}$ while the final result as given in the text was derived from a 2.2 fb$^{-1}$ data set. The lower right plot shows the top pair production cross section as a function of the top quark mass for the combination of the lepton+jets, dilepton and tau+lepton channels [13], the theory prediction from [14] and the combined $1\sigma$ likelihood.

### 3.4. Cross Section Method

The value of a quark mass is renormalization-scheme dependent. Thus it is important to extract this parameter using a well-defined renormalization scheme. Direct top quark mass measurements as discussed previously compare measured distributions to distributions simulated by leading-order MC generators as a function of the top quark mass. The input mass for these MC generators is not in a well-defined renormalization scheme leading to an uncertainty in its definition. This can be avoided when the top quark mass is extracted by comparing top pair production cross section measurements to fully inclusive theoretical calculations in higher-order QCD. They include soft gluon resummations and represent the most complete calculations available. Furthermore, they are worked out using the pole mass definition for the top quark which is thus the parameter extracted here.

The experimental and theoretical cross sections as a function of the top mass were fitted using third-order polyno-

mials in the top quark mass and Likelihoods were defined. The theoretical and experimental likelihoods are multiplied to obtain a joint likelihood as a function of the top mass. The extracted top mass is given by the minimum of the likelihood function. As an example, the combination of the $t\bar{t}$ cross sections derived in the lepton+jets [10], dilepton [11] and lepton+tau [12] decay channels as described in [13] is compared to a next-to-leading order (NLO) QCD calculation that includes all next-to-next-to-leading logarithms (NNLL) that are relevant in next-to-next-to-leading order (NNLO) QCD [14]. This is shown together with the joint likelihood in Fig. 1 (lower right). The extracted top quark pole mass is $M_{\text{top}} = 169.6\ ^{+5.4}_{-5.5}$ GeV. The total uncertainty is thus $\pm 3.2\%$.

## 4. Top Quark Mass Combinations

Taking correlated uncertainties properly into account the CDF and DØ collaborations have derived separate combinations of published Run-I (1992–1996) measurements with the most recent preliminary Run-II (2001–present) measurements using up to 2.8 $\text{fb}^{-1}$ of data. The new CDF combination [15] gives $m_{\text{top}} = 172.4 \pm 1.0(\text{stat}) \pm 1.3(\text{syst})$ GeV, the new DØ combination [16] $m_{\text{top}} = 172.8 \pm 1.0(\text{stat}) \pm 1.3(\text{syst})$ GeV. These results were combined to the new world average [17] of $m_{\text{top}} = 172.4 \pm 0.7(\text{stat}) \pm 1.0(\text{syst})$ GeV. This corresponds to a relative precision of 0.7% on the top quark mass.

## 5. Conclusions

Various measurements of the top quark mass in the lepton+jets channel and combinations with other channels were presented. The most precise measurements today are systematically limited. The main challenge right now is thus to work on reducing the experimental and theoretical uncertainties where ever possible. To get a better understanding of the interpretation of the measured quantity with respect to the applied renormalization scheme will be an important task for the future.

## References

[1] F. Abe *et al.* [CDF Collaboration], Phys. Rev. Lett. **74**, 2626 (1995) [arXiv:hep-ex/9503002].
[2] S. Abachi *et al.* [DØ Collaboration], Phys. Rev. Lett. **74** (1995) 2632 [arXiv:hep-ex/9503003].
[3] The CDF Collaboration, Conference Note 9206; T. Aaltonen *et al.*, arXiv:0809.4808 [hep-ex].
[4] The CDF Collaboration, Conference Note 9414; A. Abulencia *et al.*, Phys. Rev. D **75**, 071102 (2007).
[5] The CDF Collaboration, Conference Note 9427; A. Abulencia *et al.*, Phys. Rev. Lett. **99**, 182002 (2007).
[6] The DØ Collaboration, Conference Note 5750; V. M. Abazov *et al.*, Phys. Rev. Lett. **101**, 182001 (2008).
[7] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **75**, 092001 (2007).
[8] The CDF Collaboration, Conference Note 9414; A. Abulencia *et al.*, Phys. Rev. Lett. **96**, 022004 (2006).
[9] The DØ Collaboration, Conference Note 5742; V. M. Abazov *et al.*, Phys. Rev. Lett. **100**, 192004 (2008).
[10] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **100**, 192003 (2008).
[11] The DØ Collaboration, Conference Note 5477.
[12] The DØ Collaboration, Conference Note 5607.
[13] The DØ Collaboration, Conference Note 5715.
[14] S. Moch and P. Uwer, Phys. Rev. D **78** (2008) 034003.
[15] The CDF Collaboration, Conference Note 9450.
[16] The DØ Collaboration, Conference Note 5747.
[17] The Tevatron Electroweak Working Group and CDF and DØ Collaborations, arXiv:0808.1089 [hep-ex].